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Uptake and Fate of Triticonazole Applied as Seed Treatment to Spring Wheat (*Triticum aestivum* L.)

Rodolphe Quérou,[1]* Michel Euvrard[2] & Christian Gauvrit[1]

[1] INRA, Laboratoire de Phytopharmacie, B.V. 1540, 21034 Dijon Cedex, France
[2] Rhône Poulenc Agro, 14-20 rue Pierre Baizet, 69009 Lyon, France

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Abstract: Following seed treatment of wheat (*Triticum aestivum* L.) with ^{14}C-labelled triticonazole at a dose of 1·8 g kg^{-1} seed, the uptake of radioactivity by shoots and roots was investigated from the two- to three-leaf stage up to the beginning of the booting phase, 80 days after sowing. Triticonazole equivalents taken up by wheat plants reached 5·7% and 14·6% of the applied dose in the shoots and the roots, respectively. Between the two- to three-leaf stage and the beginning of the booting phase, the concentration of triticonazole equivalents in the shoots decreased from 2·5 to 0·15 μg g^{-1} fresh weight. This was attributed to uptake of triticonazole by roots not keeping pace with shoot growth and increased retention in the roots of triticonazole taken up. The main factor limiting the uptake of triticonazole by the roots may be the rapid growth of the uptake-active apical root parts out of the dressing zone which had formed in the soil. Distribution of triticonazole equivalents taken up by the main shoot showed a decreasing concentration gradient from the oldest to the youngest leaf. An increase in the seed treatment dose was investigated as a way to increase the concentration of triticonazole in the shoots, but its influence remained limited.

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Key words: triazole; *Triticum aestivum;* seed treatment; root uptake; shoot uptake; triticonazole

1 INTRODUCTION

Triticonazole is a broad-spectrum systemic fungicide used as wheat seed treatment against foliar diseases.[1] The efficiency of such fungicides can be related to the active ingredient (AI) concentration in the plant shoots.[2–6] The concentration in shoots of various fungicides or insecticides used as seed treatment has been reported to decrease during plant growth.[4–7] This decrease was due to a dilution of the AI taken up and to its metabolisation.[4–7] Whatever the growth stage, a decreasing concentration gradient was generally observed from the oldest to the youngest leaf.[2,4,5,7,8]

The factors influencing the uptake by the shoots of pesticides applied via seed treatment have been widely studied. From the two- to three-leaf stage up to the heading phase, systemic fungicides or insecticides applied as seed treatment to wheat or barley were taken up mainly by the roots and translocated to the shoots.[2–4,7,8] The uptake by the shoots was related to various factors including (1) soil moisture,[4,5,7] (2) growth temperature,[5] (3) physicochemical properties of the AI,[3,9] (4) the formulation of the AI[10] and (5) the dose of seed treatment.[5,6] (1) An increase in soil moisture was found to promote the translocation of triadimenol[4] and imidacloprid[7] away from the seed. This decreased the AI availability in soil and therefore its uptake by the shoots.[4,7] (2) An increase in growth temperature enhanced the uptake of triadimenol by barley shoots after seed treatment.[5] (3) Graham-Bryce *et al.*[3] reported that the fate of four carbendazim-producing fungicides used as wheat seed treatment was

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related to their water solubility and to their lipophilicity as assessed by the log *K* octanol/water partition coefficient (log K_{ow}). The more polar compounds were more concentrated in the soil solution and were therefore more available for uptake by the roots and subsequent translocation to the shoots.[3] (4) The use of controlled-release formulations for seed treatment was reported to increase the concentration of carbofuran in bean shoots.[10] (5) The uptake of triadimenol by barley shoots and the uptake of carbendazim by rice shoots has been reported to increase with increasing seed treatment dose.[5,6]

In these previous studies on seed treatment, only a few data were reported on the uptake of AIs by roots and their translocation to the shoots. The present study was aimed at measuring the release of triticonazole from the seed dressing into the soil and its subsequent uptake by wheat roots and shoots during plant growth. The distribution of triticonazole within the shoots, its metabolisation in the leaves and the influence of the seed treatment dose were also studied.

2 MATERIALS AND METHODS

2.1 Uptake and distribution of triticonazole following wheat seed treatment

2.1.1 Seed treatment

Spring wheat seeds (*Triticum aestivum* L., cv. Rex) were treated using a liquid seed-dressing formulation ('Real' 200 g litre^{-1} suspension concentrate with copolymers, Rhône-Poulenc Agro, hereafter referred to as SCcP) of [*phenyl-U*-^{14}C]triticonazole (specific activity 3·71 kBq μg^{-1}) as previously described.[11] The amount of triticonazole applied with 95% confidence interval (CI) was 81·2 (±4·6) μg per caryopsis, which is equivalent to 1·8 (±0·1) g triticonazole kg^{-1} seed.

2.1.2 Plant culture and sampling

Treated seeds were sown at 2 cm depth in plastic pots (20 cm diameter, 60 cm height, 13 seeds per pot) filled with a mixture of silt loam soil + sand (1 + 1 by volume). A wire netting basket was included in the pots to collect the soil + sand mixture to a depth of 10 cm. The pots were placed in a growth chamber at 70/80% RH, 18°C/10°C (light/dark), 16-h photoperiod (fluorescent light delivering 320 μE m^{-2} s^{-1} P.A.R.). The pots were watered weekly during the first four weeks (500 ml per pot and per week) and then daily (200 ml per pot and per day) until the last sampling time. The plants were sampled 20, 43, 60 and 80 days after sowing (DAS), corresponding to the following decimal growth stages (Zadoks *et al.*)[12]: 12–13 (two- to three-leaf stage), 23 (main shoot and three tillers), 30 (pseudostem erection) and 32–39 (beginning of the booting phase). The plants were removed with their shoots, seed and part of their roots (roots of the 0–10 cm layer of soil + sand mixture). The 0–10 cm layer of soil + sand mixture was also removed. Ten plants per pot among 13 constituted a sample. Four replicates were recovered at each sampling time.

2.1.3. Determination of radioactivity

Plant samples were divided into the following batches: leaves of the main shoot, tillers, seed and part of the roots. The first, third and fifth leaves appearing on the main shoot (hereafter referred to as F1, F3 and F5, respectively) were used for a metabolisation study (see Section 2.2). The other plant parts were weighed (fresh weight), dried overnight at 50°C and weighed again (dry weight). The samples were combusted in a Packard 306 Oxidizer and the radioactivity was measured by liquid scintillation counting (LSC) in a Beckman LS 6000 TA counter. Soil samples were air-dried, homogenised and weighed. An aliquot (100 g) was removed from each sample and extracted once with acetonitrile + water (9 + 1 by volume, 2·5 ml g^{-1} dry soil) and twice with methanol + water + ammonia (7 + 2 + 1 by volume, 2·5 ml g^{-1} dry soil). The extraction mixtures were filtered, and the filtrates were mixed and evaporated. The dry residues were redissolved with methanol + water + ammonia (7 + 2 + 1 by volume, 5 ml per sample). The radioactivity was measured by LSC on 1-ml aliquots. It was checked that these procedures did not induce triticonazole losses.

2.2 Triticonazole metabolisation in wheat leaves

The leaves F1, F3 and F5 of the main shoot (10 leaves per sample) were weighed and extracted in a mortar and pestle for 30 min with acetonitrile + water (9 + 1 by volume, 10 ml g^{-1} fresh weight). The extract was then left twice in the presence of methanol (10 ml g^{-1} fresh weight), firstly 30 min at room temperature, secondly overnight at 4°C. The extraction mixtures were filtered. The non-extractable radioactivity in the residue on the filters was measured by LSC after combustion and was considered as metabolites. The filtrates were mixed, the volume was measured and the radioactivity was determined by LSC using 1-ml aliquots. The filtrates were evaporated and the dry residues were redissolved with dichloromethane (5 ml) and then with water (10 ml). The aqueous phase was extracted with dichloromethane (3 × 5 ml) in a separatory funnel. The radioactivity in the aqueous phase was then measured by LSC using 1-ml aliquots. It was previously verified that after this clean-up procedure, all the radioactivity in the aqueous phase was metabolites. The organic phases were mixed and evaporated. The dry residues were redissolved with ethyl acetate (0·1 to 0·5 ml). The radioactivity in these solutions was measured using 20-μl aliquots. The samples were analysed by thin layer chromatography (TLC) using precoated plates (Merck silica gel 60,

0·25 mm thickness, 200 mm plates). Aliquots (50–150 µl) were deposited on the plate and eluted with acetone + petroleum ether (40–65°) (1 + 1 by volume). Evaluation was performed with a scanner (Isomess Stratec). The metabolites were not identified, but the unmetabolised triticonazole was identified by comparison with a standard deposited on each plate. The amount of unmetabolised triticonazole was calculated as a percentage of the radioactivity taken up.

2.3 Influence of the seed-treatment dose

Winter wheat seeds (cv. Thésée) were treated by the method previously described[11] with a liquid seed-dressing formulation of [^{14}C]triticonazole. Two suspension concentrate formulations, SC1 and SC2, differing in the concentration of AI, were used for the treatments. Both were similar to the SCcP formulation, except that they did not include copolymers. Three batches of seeds (10 g each) were treated at 0·45, 0·6 and 0·9 g AI kg^{-1} seed with a 60 g AI litre^{-1} suspension concentrate (SC1). Two batches of seeds (10 g each) were treated at 1·2 and 2·4 g AI kg^{-1} seed with a 200 g AI litre^{-1} suspension concentrate (SC2). [^{14}C]Triticonazole was 11·4% of the total amount of triticonazole for SC1 and 3·7% for SC2. The treatments were performed by mixing appropriate amounts of SC with water to give a 0·2-ml application slurry. The amounts of triticonazole applied (determined on 20 caryopses per dose) with 95% confidence interval were 23·5 (±1·6), 28·4 (±1·9), 48·2 (±3·5), 63·3 (±2·7) and 130·4 (±15·5) µg per caryopsis, which is equivalent to 0·48 (±0·03), 0·60 (±0·03), 0·98 (±0·06), 1·22 (±0·06) and 2·59 (±0·35) g kg^{-1} seed, respectively.

The treated seeds were sown in plastic pots (20 cm diameter, 16 cm height, 13 seeds per pot, 1 pot per dose) filled with a mixture of silt loam soil + sand (1 + 1 by volume). The plants were grown as described in Section 2.1.2. Plants with their shoots, seed and roots were sampled 20 DAS at the decimal growth stage 12–13 (two- to three-leaf stage).[13] The soil + sand mixture of each pot was also collected. For each treatment dose, six plants of homogenous development were selected per pot. Each plant was divided into batches: shoots, seed and roots. The amounts of radioactivity in these batches and in soil samples were determined as described in Section 2.1.3.

All the results are given as arithmetic means with 95% confidence intervals (CI).

3 RESULTS

3.1 Uptake and distribution of triticonazole following wheat seed treatment

3.1.1 Release of triticonazole from the seed dressing into the soil

The amount of radioactivity (triticonazole equivalents) on the caryopsis decreased from 100% to 57% of applied label, from sowing up to 43 DAS (growth stage 23, mid-tillering stage) (Table 1). From 43 up to 80 DAS (growth stage 32–39, beginning of the booting phase), the amount of triticonazole equivalents on the seed decreased slightly. At the last sampling time, 44% of the applied radioactivity was still on the caryopsis. The amount of extractable triticonazole equivalents in the soil reached 25% 43 DAS and showed little variation from 43 up to 80 DAS.

3.1.2 Uptake of triticonazole by wheat plants

The amount of triticonazole equivalents taken up by the roots increased from sowing up to 80 DAS and reached 12 µg per plant (Fig. 1(a)), which was 15% of applied triticonazole (Table 1). In the same time, the fresh weight of the roots (fraction of the 0–10 cm layer of soil + sand mixture) reached about 9 g per plant, 80 DAS. As shown in Fig. 1(b), the amount of triticonazole equivalents taken up by the shoots increased linearly from sowing up to 80 DAS (linear regression, $R^2 = 0{\cdot}95$) and reached 5 µg per shoot, which was 6% of applied triticonazole (Table 1). In the same time, the fresh weight of the shoots reached 30·5 g per plant. The concentrations of triticonazole equivalents in the shoots and in the roots were very close at the two- to three-leaf

TABLE 1
Distribution of Radioactivity on Seed, in Soil and in Wheat Plants following Seed Treatment with [^{14}C]triticonazole

		AI equivalent (% of applied dose)[a]				
DAS	*Growth stage*	*Caryopsis*	*Soil*	*Roots*	*Shoots*	*Recovery*
0	00	100	—	—	—	—
20	12–13	74·6 (±11·4)	23·0 (±3·0)	0·8 (±0·1)	1·0 (±0·1)	99·5 (±9·9)
43	23	56·6 (±5·5)	24·6 (±6·4)	4·0 (±0·6)	2·9 (±0·3)	88·1 (±4·3)
60	30	50·9 (±6·3)	26·8 (±4·8)	11·5 (±4·1)	4·6 (±1·0)	95·2 (±5·6)
80	39	43·9 (±9·1)	27·3 (±0·6)	14·6 (±2·5)	5·7 (±0·8)	89·4 (±5·7)

[a] Mean values of four replicates (10 plants for each replicate) with 95% CI.

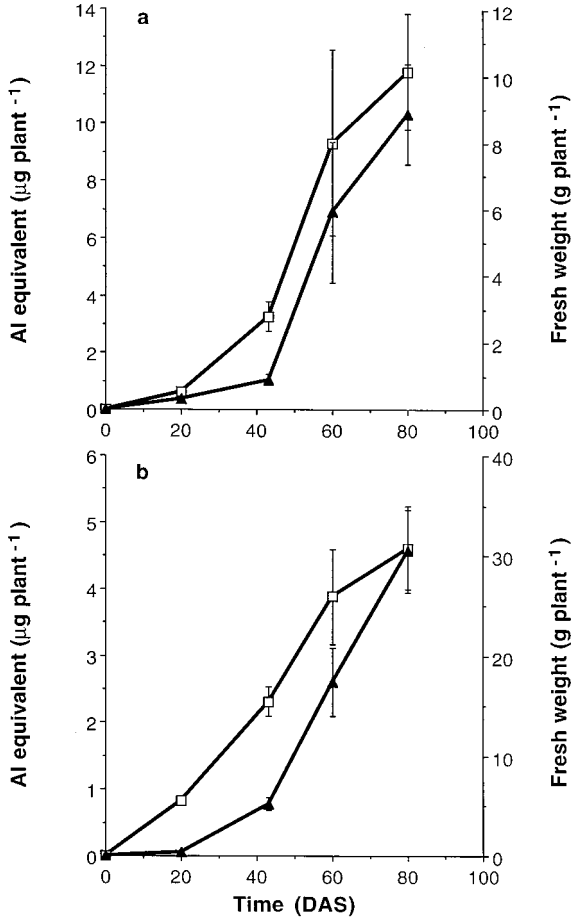

Fig. 1. Uptake of radioactivity (AI equivalents) (a) by wheat roots; (▲) fresh weight of the roots, and (b) by wheat shoot; (▲) fresh weight of the shoot following seed treatment with [^{14}C]triticonazole. DAS = Days After Sowing. Mean values of four replicates (10 plants for each replicate). Vertical bars represent 95% CI.

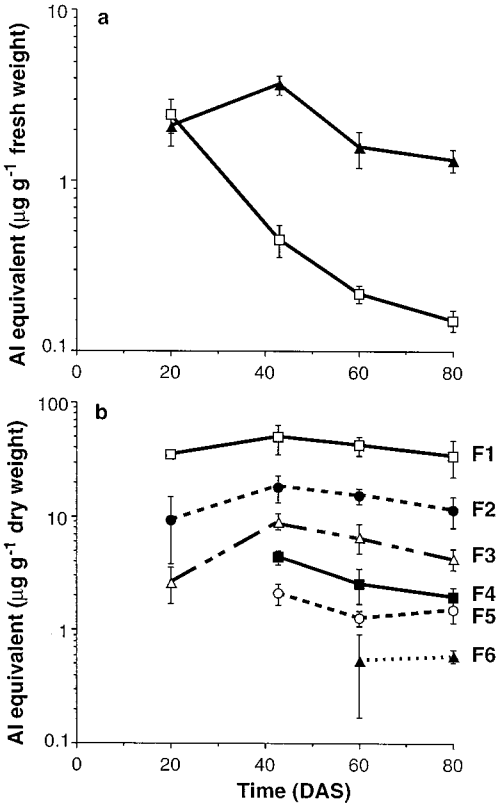

Fig. 2. Concentration of AI equivalents (a) in (□) shoot and (▲) roots, and (b) in six leaves of the main shoot of wheat plants following seed treatment with [^{14}C]triticonazole. Log scale. DAS = Days After Sowing. Mean values of four replicates (10 plants for each replicate), vertical bars represent 95% CI.

stage, 20 DAS (Fig. 2(a)). From 20 up to 80 DAS, the concentration of triticonazole equivalents in the shoots dropped sharply from 2·5 to 0·15 µg g^{-1} fresh weight. Over the same time, the concentration in the roots firstly increased from 2·1 to 3·7 µg g^{-1} fresh weight and then decreased to 1·3 µg g^{-1} fresh weight. From 20 up to 80 DAS, the amount of triticonazole equivalents in the roots, relative to the amount taken up by the whole plant (shoots + roots) increased from 43 (±5·5)% to 71·8 (±5·7)% (data not shown).

3.1.3. *Distribution of triticonazole within the shoots*

The amount of triticonazole equivalents taken up by the main shoot increased from sowing up to 43 DAS (growth stage 23) and showed little variation from 43 up to 80 DAS (growth stage 32–39) (Table 2). Whatever the growth stage, the amount of triticonazole equivalents taken up by each tiller increased during its growth but remained lower than that of the main shoot. At each sampling time, the amount of triticonazole equivalents taken up decreased from the main shoot to the youngest tiller. The amount of triticonazole equivalents taken up by the leaves F1, F2 and F3 of the main shoot increased up to 43 DAS and then decreased from 43 up to 80

TABLE 2
Radioactivity Uptake by the Main Shoot and the Tillers of Wheat Plants following Seed Treatment with [^{14}C]triticonazole

		AI equivalent (µg plant^{-1})[a]					
DAS	*Growth stage*	*Main shoot*	*1st tiller*	*2nd tiller*	*3rd tiller*	*4th tiller*	*5th tiller*
20	12–13	0·83 (±0·05)	—	—	—	—	—
43	23	1·86 (±0·17)	0·26 (±0·13)	0·13 (±0·02)	0·06 (±0·03)	—	—
60	30	1·92 (±0·26)	0·70 (±0·14)	0·43 (±0·13)	0·42 (±0·14)	0·19 (±0·11)	0·11 (±0·10)
80	39	2·09 (±0·31)	0·83 (±0·38)	0·64 (0·15)	0·47 (±0·25)	0·30 (±0·14)	0·16 (±0·15)

[a] Mean values of four replicates (10 plants for each replicate) with 95% CI.

TABLE 3
Radioactivity Uptake by Six Leaves of the Main Shoot of Wheat Plants following Seed Treatment with [^{14}C]triticonazole

		AI equivalent (μg plant^{-1})[a]					
DAS	*Growth stage*	*1st leaf*	*2nd leaf*	*3rd leaf*	*4th leaf*	*5th leaf*	*6th leaf*
20	12–13	0·46 (±0·06)	0·16 (±0·09)	0·05 (±0·02)	—	—	—
43	23	0·55 (±0·10)	0·31 (±0·06)	0·33 (±0·04)	0·29 (±0·05)	0·27 (±0·03)	—
60	30	0·44 (±0·08)	0·29 (±0·03)	0·30 (±0·04)	0·30 (±0·06)	0·26 (±0·04)	0·14 (±0·07)
80	39	0·34 (±0·14)	0·20 (±0·03)	0·18 (±0·04)	0·21 (±0·05)	0·28 (±0·04)	0·18 (±0·03)

[a] Mean values of four replicates (10 plants for each replicate) with 95% CI.

DAS (Table 3). The amount of triticonazole equivalents taken up by the leaves F4, F5 and F6 of the main shoot showed little variation from the first sampling date up to 80 DAS. The amount of triticonazole equivalents taken up was higher in F1 than in the other leaves. Figure 2(b) shows the concentration of triticonazole equivalents in six leaves of the main shoot expressed as μg g^{-1} dry weight. Dry weight was preferred to fresh weight in order to avoid any artifact due to water loss in tissues of the senescing leaves. The concentration of triticonazole equivalents in the leaves F1, F2 and F3 increased from 20 up to 43 DAS and then decreased from 43 up to 80 DAS. In the leaf F4, the concentration decreased from 43 up to 80 DAS. For the leaves F5 and F6, the concentration showed little variation. The decrease in concentration of triticonazole equivalents in the leaves F1, F2, F3 and F4 was associated to losses of triticonazole equivalents (Table 3) and to losses of dry matter (data not shown) associated with the senescence of the leaves. Whatever the growth stage, a decreasing concentration gradient was observed from the oldest to the youngest leaf of the main shoot. At 80 DAS, the concentration ratio F1 : F6 was 58 : 1.

3.2 Triticonazole metabolisation in wheat leaves

At each sampling time, the proportion of unmetabolised triticonazole, relative to total radioactivity taken up (extractable + non-extractable), was not significantly

TABLE 4
Proportion of Unmetabolised Triticonazole in Three Leaves of the Main Shoot of Wheat Plants following Seed Treatment with [^{14}C]triticonazole

		Unmetabolised triticonazole (% of ^{14}C taken up)[a]		
DAS	*Growth stage*	*1st leaf*	*3rd leaf*	*5th leaf*
20	12–13	78·6 (±6·2)	83·9 (±2·8)	—
43	23	73·1 (±5·1)	73·4 (±5·7)	77·6 (±4·8)
60	30	68·5 (±10·7)	68·0 (±11·3)	66·5 (±9·3)
80	39	58·0 (±7·8)	61·4 (±10·1)	56·2 (2·7)

[a] Mean values of four replicates (10 plants for each replicate) with 95% CI.

TABLE 5
Distribution of Radioactivity on Seed, in Soil and in Wheat Plant 20 Days after Sowing, following Seed Treatment with [^{14}C]triticonazole at Various Doses

Dose rate (g kg^{-1})	*AI equivalent (% of applied dose)*[a]				
	Caryopsis	*Soil*[b]	*Roots*	*Shoot*	*Recovery*
0·45	14·0 (±10·1)	66·2	1·4 (±0·3)	4·5 (±1·0)	86·1 (±10·8)
0·6	6·8 (±5·2)	65·1	1·0 (±0·3)	2·5 (±0·7)	75·5 (±5·6)
0·9	33·9 (±15·4)	54·3	0·9 (±0·2)	3·2 (±0·3)	92·3 (±15·3)
1·2	37·9 (±7·2)	49·9	1·0 (±0·6)	2·4 (±0·5)	91·3 (±6·5)
2·4	53·1 (±17·1)	31·5	1·3 (±0·8)	1·6 (±0·3)	87·4 (±16·6)

[a] Mean values of six replicates (one plant by replicate) with 95% CI.
[b] Single value of one pot by dose.

different between the leaves F1, F3 and F5 (Table 4). For each leaf, the proportion of unmetabolised triticonazole decreased with time. For example, from 20 up to 80 DAS, it decreased from 79% to 58% in F1 and from 84% to 61% in F3. In F5, it decreased from 78% to 56% between 43 and 80 DAS. In the roots, unmetabolised triticonazole amounted to about 90% of the radioactivity measured 80 DAS.[14]

3.3 Influence of the seed treatment dose

The influence of treatment dose was studied on winter wheat at growth stage 12–13 (two- to three-leaf stage), 20 DAS. Table 5 shows the distribution of triticonazole equivalents in various parts of the soil–plant system 20 DAS. When the treatment dose increased from 0·45 to 2·4 g triticonazole kg^{-1} seed, the proportion of triticonazole equivalents on the caryopsis increased from 14% to 53% of the amount applied and the proportion of triticonazole equivalents in the soil decreased from 66% to 32%. The proportion of triticonazole equivalents taken up by the roots showed little variation whatever the dose applied. The proportion of triticonazole equivalents taken up by the shoots decreased from 4·5% to 1·6% of the amount applied when the dose increased from 0·45 to 2·4 g kg^{-1} seed. By comparing the results of Table 5 and Table 1, it can be observed that, 20 DAS, the release of triticonazole in soil (as a percentage of the dose applied) was higher in the dose experiment (32% to 66%) than in the previous experiment (23%). As shown in Fig. 3, when the treatment dose increased from 0·45 to 2·4 g triticonazole kg^{-1} seed, the concentration of triticonazole equivalents in the roots increased from 0·8 to 3·8 μg g^{-1} fresh weight and in the shoots from 2·2 to 4·8 μg g^{-1} fresh weight. A curvilinear relationship ($R^2 = 0{\cdot}80$) was found between the concentrations of triticonazole equivalents in the shoots and in the roots (data not shown). By comparing

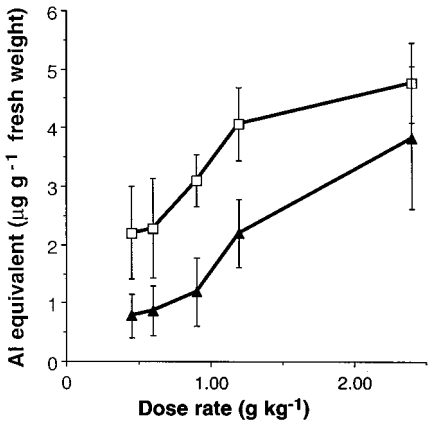

Fig. 3. Concentration of AI equivalents in (□) shoot and (▲) roots of wheat plants 20 days after sowing, following seed treatment with [^{14}C]triticonazole at various doses. Mean values of six replicates of one plant. Vertical bars represent 95% CI.

the results of Figs 2(a) and 3, it can be observed that, 20 DAS, the concentration of triticonazole equivalents in the shoots was 3·1 (±0·44) μg g^{-1} fresh weight for the dose of 0·9 g kg^{-1} seed, which is similar to the concentration measured in the previous experiment (2·46 (±0·57) μg g^{-1} fresh weight) with twice the dose (1·8 g kg^{-1} seed).

4 DISCUSSION

Following seed treatment of wheat with triticonazole at a dose of 1·8 g kg^{-1} seed, the amount of triticonazole equivalents released from the seed dressing into the soil increased from sowing up to 43 DAS, and then only slightly between 43 and 80 DAS. At the beginning of the booting phase, 80 DAS, about 44% of the applied triticonazole was still on the seed. This differed from previous studies on triadimenol and imidacloprid.[4,7,8] After seed treatment of wheat and barley with triadimenol at a dose of 0·4 g kg^{-1} seed, about 10% of the amount applied remained on the seed 50 to 70 DAS.[4,8] After seed treatment of winter wheat with imidacloprid at a dose rate of 1 g kg^{-1} seed, the amount of imidacloprid on the seed 111 DAS increased from 2 to 16% of the dose applied when the soil moisture decreased.[7] The lower release of triticonazole into soil may be due to various factors, including (1) soil moisture, (2) water solubility of the AI, (3) treatment dose and (4) the formulation used. (1) Watering (450 mm) in our study was higher than rainfall in the studies on triadimenol (120 to 205 mm)[4,8] but, since the actual soil moisture was not measured in either experiment, no comparison can be made. (2) Triticonazole solubility in water (7 mg $litre^{-1}$)[14] is lower than that of triadimenol (32 to 62 mg $litre^{-1}$)[15] and imidacloprid (510 mg $litre^{-1}$).[16] This probably limited its removal by water from the seed dressing. (3) In our study, triticonazole was applied at a dose rate of 1·8 g kg^{-1} seed, higher than the dose used for triadimenol (0·4 g kg^{-1} seed) and imidacloprid (1 g kg^{-1} seed).[4,7,8] This difference may partly explain the higher retention of triticonazole on the seed, in agreement with our observation that, 20 DAS, the higher the dose rate, the lower the proportion of triticonazole released into soil. (4) Finally, the type of formulation used may have influenced the removal of the AI by water, as described for triflumizole.[17] Triticonazole was applied using a suspension concentrate, triadimenol was applied using a dry seed-dressing formulation and imidacloprid was applied using a water-dispersible powder.[4,7,8] The copolymers used in the SCcP formulation of triticonazole may also have acted as controlled-release agents, since we observed at the two- to three-leaf stage a higher release of triticonazole into soil with the SC1 and SC2 formulations (without copolymers) than with the SCcP formulation (with copolymers). However, the difference in height of the

pots used in the two experiments (16 versus 60 cm, respectively) may have influenced soil moisture by a drainage effect.

The amount of triticonazole equivalents found in wheat plants (roots + shoots) reached 20% of applied fungicide (16 μg per plant) 80 DAS. This can be compared to results of similar experiments involving other seed-treatment compounds. The uptake of four carbendazim-producing fungicides was investigated 28 DAS after seed treatment of barley at a dose rate of 300 μg per seed (equivalent to a dose rate of 6–7 g kg^{-1} seed).[3] The amount found in barley plants increased from 1·3 to 9% of the dose applied (4 to 27 μg per plant) when the water solubility of the AI increased and its lipophilicity decreased.[3] After seed treatment of spring wheat or spring barley with triadimenol at a dose of 0·4 g kg^{-1} seed, the amount found in plants was 8–9% (1–1·4 μg per plant) 51 DAS. In the case of winter cereals, it lay between 4 and 12% of the applied dose (0·7–2·2 μg per plant) up to 180–215 DAS, depending mainly on rainfall distribution.[4,8] After seed treatment of winter wheat with imidacloprid at a dose of 1 g kg^{-1} seed, 9–21% of the applied dose (from 4 to 10 μg per plant) was recovered in plants when soil moisture decreased from 50 to 30% of the water holding capacity.[7] Hence, the amounts of triticonazole taken up by wheat plants following seed treatment were in the same range as other seed treatment compounds.

We showed previously that the pathway from seed coats to endosperm to scutellum to shoots is not an important route for triticonazole uptake by shoots.[11] An alternative route is *via* uptake by roots from the dressing zone in the soil in the vicinity of the seed.[4,7] Because of its physicochemical properties ($K_{OC_{ad}}$ = 184–563, $K_{OC_{des}}$ = 200–654),[18] triticonazole has a low mobility in soil and its dressing zone is expected to be of small size, as described for ethirimol.[2] Since uptake of soil solution by roots takes place mainly at the level of apical parts, the growth of the latter out of the dressing zone would result in a decrease in triticonazole uptake. Indeed, previous studies on the uptake of systemic pesticides by roots reported that, when plants were grown on soil, uptake was more effective at the apical zone of the roots than at the basal suberinized zone.[2,4,7] Similarly, the linear uptake of triticonazole by the shoots may result from a steady emission of young roots in the dressing zone. We observed previously that, during the growth of a wheat plant, uptake-active young roots were always found near the seed, with the successive emergence of seminal, nodal and side roots.[13] This hypothesis disagrees with results of previous studies since Thielert *et al.*[4] and Stein-Dönecke *et al.*[7] reported that enlargement of the dressing zone of triadimenol and imidacloprid in soil decreased their root uptake. In these cases, the seed reservoirs of AI were rapidly exhausted. The enlargement of the dressing zone and the AI uptake by roots resulted in a decrease of the concentration of the latter in the soil solution.[4,7] Under these conditions, the limiting factor may be the dose of seed treatment. In the case of triticonazole, we observed a slow release into soil. The amount of AI on the seed was not a limiting factor, since 44% of the applied AI was still on the seed 80 DAS and because it has a low mobility in soil. As a result, its concentration in the vicinity of the seed may show little variation. Under these conditions, the limiting factor may be the size of the dressing zone in soil.

The translocation from roots to shoots of an AI is closely related to its uptake by the roots. Using various doses of seed treatment at the two- to three-leaf stage, a correlation was found between the concentration of triticonazole equivalents in the shoots and in the roots. This observation suggests that, even between sowing and the two- to three-leaf stage, the amount of triticonazole equivalents found in the shoots was related to the uptake by the roots. It confirms previous results on triticonazole[11] and on some carbendazim-producing fungicides.[3] However, due to increasing retention in roots, the translocation of triticonazole to the shoots decreased from 57 to 28% of the amount taken up, from 20 to 80 DAS. Strang and Rogers[19] observed that, after root treatment of cotton and soybean, ^{14}C-labelled trifluralin was retained on the root surface by binding to the epidermis. In addition, its entrance into the roots was facilited by breaks in the epidermis. Briggs *et al.*[20] reported that, in barley, translocation of lipophilic compounds from roots to shoots was limited by partitioning into lipophilic root domains. Barak *et al.*[21] found that lignin adsorbed systemic fungicides. Adsorption increased with lipophilicity of the fungicides[21] and limited their translocation to the leaves.[22] Suberin is well known to adsorb lipophilic compounds[23] and can therefore be expected to act in the same way as lignin. Accordingly, the increase in triticonazole root retention with time may be due to the increase in the surface of suberinized root tissues in the dressing zone. For carbendazim-producing fungicides, triadimenol and imidacloprid, root retention was 50–90, 10–15 and 5–11%, respectively.[3,4,7,8] Using hydroponic cultures, Briggs *et al.*[20] reported that, in barley, translocation from roots to shoots of various pesticides was maximal for compounds of intermediate polarity (log K_{OW} between 1·5 and 2). However, the amount of carbendazim-producing fungicides found in shoots increased with increasing water solubility and decreasing lipophilicity of the AI.[3] In addition, triticonazole and triadimenol were retained in roots to different extents, about 70% and 10–15%, respectively, although they have similar K_{OW} values (3·29 and 3·08, respectively)[14,15] and were reported not to be metabolised in roots. Finally, imidacloprid has a log K_{OW} of 0·57[16] and displays similar retention to triadimenol. Hence, retention in roots may not be related only to lipophilicity.

The concentration of triticonazole equivalents in the shoots dropped sharply between the two- to three-leaf stage and the beginning of the booting phase. Similar results were reported about triadimenol, imidacloprid and carbendazim.[4–7] In the main shoot, at each sampling time, a decreasing concentration gradient of triticonazole equivalents was observed from the oldest to the youngest leaves. The concentration ratio F1 : F6 reached 58 : 1 80 DAS. Similar results have been reported for ethirimol, triadimenol and imidacloprid used as seed treatment on wheat or barley and are characteristic of xylem-mobile substances.[2,4,5,7,8] The linear uptake with time of triticonazole equivalents by the shoots was not sufficient to maintain a constant concentration. This could be due, first, to an insufficient root uptake (caused by the growth of apical root parts out of the dressing zone in soil) and, second, to an increase in root retention as discussed above. For example, from 43 DAS up to 80 DAS, the amount of triticonazole equivalents taken up by the shoots doubled, whereas fresh weight increased 6-fold. In addition, retention of triticonazole equivalents in the roots increased from 43% of the radioactivity taken up 20 DAS to 72% 80 DAS. Increasing the dose of seed treatment increased AI equivalent concentration in the shoots, at least at the two- to three-leaf stage. However, this influence was limited, since doubling the dose from 1·2 to 2·4 g kg^{-1} resulted only in a 17% increase of AI equivalent concentration at the two- to three-leaf stage.

Triticonazole metabolisation was determined in three leaves of the main shoot. The parent compound represented 56–61% of total radioactivity 80 DAS. This result may be an underestimation, since we observed radioactivity losses during leaf senescence, which may have been preferential losses of metabolites by guttation or losses of leaf tissues. Metabolisation decreased the concentration of triticonazole in leaves. However, the concentration ratio of total radioactivity between leaves F1 and F6 was 58 : 1. Hence, triticonazole metabolisation had very probably a lower influence on triticonazole concentration than dilution in growing plant tissues. In addition, unmetabolised triticonazole represented about 90% of the radioactivity measured in the roots 80 DAS.[13] Finally, after foliar treatment with [^{14}C]triticonazole, the parent compound comprised about 50% of triticonazole in the leaves 60 DAS.[13] This proportion is similar to the one we found 80 DAS in the case of seed treatment. These results suggest that triticonazole metabolisation occurred essentially in the leaves.

5 CONCLUSION

Following seed treatment of wheat with triticonazole, the active ingredient was taken up by the roots and translocated to the shoots of developing plants. The concentration of triticonazole in the shoots decreased in the course of time. This dilution was due partly to triticonazole metabolisation in the leaves but mainly to decreasing uptake by the shoots, relative to their growth. The decrease of triticonazole uptake by the roots may be due to the rapid growth of the uptake-active apical root parts out of the dressing zone which had formed in the vicinity of the seed. Increasing the dose of seed treatment only marginally increased triticonazole concentration in the shoots at the two- to three-leaf stage.

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